The Promises of Nanotechnology: Will They Be Kept?

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Abstract

What are the mission applications of microspacecraft and nanospacecraft? What are the technology needs to enable these missions? What work is currently being done, and what is the state-of-the-art? What are the challenges?

This presentation provides an overview of National Aeronautics and Space Administration's (NASA) microspacecraft and nanospacecraft mission applications. A survey of the state-of-the-art and an overview of current development activities are provided in addition to identifying the technologies needed to enable these mission applications. Technical challenges particular to NASA micro/nanospacecraft missions are discussed.

1. Background/Introduction

Why is NASA interested in micro/nanospacecraft? Because micro/nanospacecraft are expected to be cheaper to build and fly than conventional spacecraft, and because they can provide greatly reduced launch costs through the use of smaller launch vehicles, shared launches, and/ or secondary launch opportunities [Reference 1]. For NASA, these benefits make it possible to fly more frequent, smaller missions instead of one-per-decade "flagship" missions like Galileo or Cassini. And constellations or formations of these small spacecraft can be robust to loss of any individual element, suffering small degradations to overall mission performance rather than failure of the entire mission.

2. Overview of NASA Mission Applications of Micro/Nanospacecraft

Applications and concepts for micro/nanospacecraft can be found throughout all areas of NASA's endeavor (even Human Space Flight). Applications are particularly driven where mass is severely constrained (i.e., missions to the outer planets), risk is high (in the case of uncertain or hostile environments), or where simultaneous and/or distributed measurements are needed or desirable. The following paragraphs contain descriptions (listed by Directorate) of NASA's micro/nanospacecraft applications.

2.1 Earth Science (Code Y)

Concepts of interest to NASA's Earth Science Enterprise (ESE) include constellations or formations of micro/nanospacecraft for distributed or high-temporal resolution measurements [Reference 2]. Current ESE mission concepts that utilize microspacecraft include:

- Radio Occultation Global Positioning System: 6–100 spacecraft, 30-kg class
- Leonardo (bi-directional reflectance distribution function measurement): 6–12 spacecraft, 30- to 100-kg class
- Global Precipitation Mission: 3–9 spacecraft (plus core), 50-kg class.

For micro/nanospacecraft constellations, formation flight using micropropulsion is a key enabling technology. Several autonomy technologies are also enhancing or enabling for constell-ations, including autonomous navigation, relative navigation and collision avoid-ance, collective planning and scheduling, collective pointing, and fault diagnosis and recovery.

2.2 Space Flight (Code M)

In recent years, NASA's Johnson Space Center (JSC) and Ames Research Center (ARC) have been pursuing the development of robotic astronaut assistants and environmental monitors for the Space Shuttle and the International Space Station (ISS). The Autonomous EVA Robotic Camera (AERCam) Sprint is a 35-cm diameter, 16-kg microspacecraft, which was flown on STS-87 in 1997 [Reference 3]. Another concept under dev-elopment at ARC is the Personal Satellite Assis-tant (PSA) [Reference 4]. Intended as a "robotic assistant for astronauts working in space," the PSA (fig. 1) has a ~15-cm diameter.

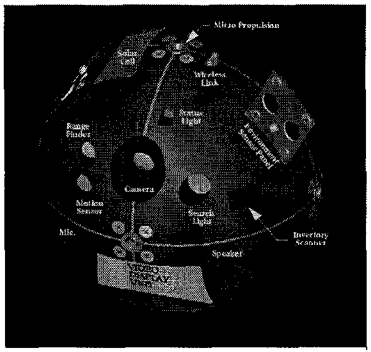

Figure 1. The PSA

Key enabling technologies for systems like the PSA and AERCam include autonomous nav-igation/maneuvering, and mobility or micro-propulsion. In the future, evolving micro/nano-sensor technologies could reduce the size and expand the capabilities of such robotic assistants.

2.3 Aerospace Technology (Code R)

Code R's interest in micro/nanospacecraft is more from the perspective of developing the necessary technology than for actual mission applications. As part of their Cross-Enterprise Technology Development Program, Code R's

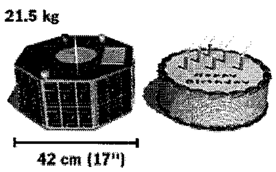

Figure 2. The ST5 spacecraft

metry [Reference 14]. The Nanosat Constellation Trailblazer, or ST5 Mission, will attempt to fly three miniature spacecraft high above the Earth to test methods for operating a constellation of spacecraft as a single system (fig. 2) [Reference 15]. The Air Force's TechSat 21 Program will demonstrate formation flight for the purpose of performing synthetic aperture radar imaging [Reference 12]. The MIT Space Systems Laboratory is developing the SPHERES (Synchronized Position Hold Engage and Reorient Experimental Satellites) to provide the Air Force and NASA with a testbed for the validation of metrology, control, and autonomy technologies [Reference 16].

3.2 *Autonomy Technologies*

Many autonomy technologies will be demonstrated by the programs described in section 4.1. Others that can reduce the need for uplink or downlink of large volumes of data include autonomous navigation, on-board data processing, and autonomous image recognition [Reference 17]. Autonomous Optical Navigation was demonstrated on the NMP Deep Space 1 (DS1) mission [Reference 18].

3.3 *Micropropulsion*

Micropropulsion research has focused on systems which utilize vaporized liquid or solid propellants which are easily stored and do not have the leakage problems associated with pressurized systems [References 19, 20]. Two examples are the subliming solid microthruster and vaporizing liquid microthruster. In addi-tion, many missions require fine pointing control, leading to a requirement for microthruster minimum impulse bit sizes $<10^{-4}$ Ns .

3.4 *Microgyros*

In recent years, teams at JPL, UCLA, and the Charles Stark Draper Laboratory have developed microgyros suitable for use in inertial guidance systems for micro/nanospacecraft (fig. 3) [Reference 21]. These devices enable several orders-of-magnitude reduction in attitude control system mass.

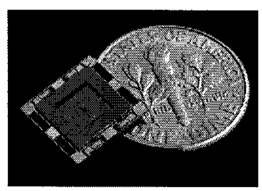

Figure 3. Microgyro

3.5 *Micro- and Nano- Instruments and Sensors*

Reductions in the mass, volume, and power requirements for the science instrument payloads are fundamentally enabling or enhancing for micro/nanospacecraft. JPL's Center for Integrated Space Microsystems (CISM) and Center for

Micro/Nano Sciencecraft Thrust Area aims at producing an orders-of-magnitude reduction of the size and mass of NASA's spacecraft [Reference 5].

2.4 Space Science (Code S)

Code S is interested in micro/nanospacecraft for missions to the outer planets, distributed and/or simultaneous sensing, *in situ* measurements and sensing, and auxillary spacecraft. Code S has participated in joint microspacecraft mission concept developments with the Air Force and with the National Oceanic and Atmospheric Administration (NOAA) [References 6, 7]. Code S Mission Concepts that utilize micro/nanospacecraft include:

- Magnetospheric Constellation [Reference 8]
- Starlight [formerly Space Technology 3 (ST3), Reference 9].

For Solar System Exploration, two of the biggest technology challenges for micro/ nanospacecraft are data collection and data return. Micro/nanospacecraft typically have size limitations on the instruments they can carry. This limits achievable sensitivity and resolution for science observations. Constellations and formation flight may provide one possible solution to this challenge, but a more fundamental solution would be provided by lightweight or deployable apertures. Lightweight or deployable apertures would also address the second challenge—data return. High-speed downlinks for large volumes of science data require high frequencies and/or high power and/or large apertures. This is particularly true for missions to the outer solar system [Reference 10].

3. Current Development Activities

Major microspacecraft technology development programs in the U.S. include:

- NASA's New Millennium Program (NMP) [ST3 (Starlight) and Space Technology 5 (ST5) missions] [Reference 9, 11]
- Air Force's TechSat 21 Program [Reference 12]
- Air Force Office of Scientific Research (AFOSR) and the Defense Advanced Research Projects Agency (DARPA) University Nanosatellite Program [Reference 13].

A summary of current development activities by technology area follows.

3.1 Formation Flight

The NMP ST3 (Starlight) Mission, scheduled for launch in 2005, will demonstrate formation flight for the purposes of long-baseline optical interfero-

4. Challenges, Issues, and Evolving Paradigms

4.1 Technical Challenges

Radiation, Micrometeoroids and Dust. Conventional (large) spacecraft often rely on a few millimeters of structural aluminum and burying electronics deep within a spacecraft bus to provide radiation shielding to sensitive electronics. Micro/nanospacecraft will not have millimeters of structural material to provide this protection, and may require selective and/or local shielding of radiation-sensitive elements. Similarly, micro/nanospacecraft will also be more vulnerable to damage by dust or micrometeoroids.

Thermal Control. Thermal time constants are much faster in small spacecraft, making thermal control more challenging. Adaptive thermal control systems are needed to accommodate widely varying thermal environments or large variations in internal heat dissipation. The dissipation of heat in compact electronics is a particular challenge for micro/nanospacecraft. New technologies providing solutions to these challenges include miniature active cooling loops, thermoelectric cooling devices, micro heat pipes, and electrochromic materials [Reference 32].

4.2 New Paradigms for Micro/Nanospacecraft Design

As we gain experience in the design of micro/nanospacecraft, new "paradigms" are emerging.

Minimize the Payload Requirements. In addition to utilizing new developments in micro- and nano-instruments, approaches such as utilizing shared front-end optics among instruments can provide major benefits.

Minimize the Telecom Requirements. Data compression technologies and onboard processing of data are two approaches to reducing downlink demands. Significant savings were also achieved in the Second Generation Microspacecraft concepts through the total elimination of uplink capability [Reference 33].

Take Advantage of Multiple-Use Technologies. Very large mass, volume, and power savings have been demonstrated in concepts that utilize the same hardware to perform multiple functions. Examples include the use of minimum gage propellant tanks or high pressure tubing as load carrying structure and dual use of optical apertures for communications and sensing. Active Pixel Sensor (APS) arrays [Reference 34] can be utilized for multiple sensing functions ranging from star tracking (sensing dim sources) to imaging of bright targets, thus eliminating the need for multiple detectors. APS arrays can also be fabricated with on-chip processing functions such as centroiding, reducing

Space Microelectronics Technology (CSMT) at have been developing microsensors, instruments, and other integrated "systems-on-a-chip". [References 22, 23]

3.6 Data Compression Technologies

Data Compression Technologies provide another option for reducing downlink requirements. The current state-of-the-art for "lossless" data compression is about 2:1, however research is ongoing into techniques that can achieve 1–2 orders-of-magnitude compression with some loss [Reference 24].

3.7 Deployable Apertures

Currently, mesh deployable antennas, such as the 12-m antennas built by Harris Corporation and flown on the ACES communications satellite [Reference 25] and the 12.25 m x 16 m antennas built by TRW Astro Aerospace for the Thuraya Satellite [Reference 26], are the state-of-the-art for deployable RF communications antennas. However, the emerging technology of inflatable antennas offers potential for compact stowage of low-mass deployable spacecraft reflectors that are compatible with micro/nanospacecraft [References 27, 28].

3.8 Optical Communications

In some applications, optical communications systems can provide indirect savings in overall spacecraft mass via reduction in power system requirements as compared with an equivalent data-rate RF system [Reference 29]. Optical communications also present the spacecraft designer with the option of using the same front-end optics for both sensing and communications ("dual-use"), potentially resulting in significant system mass savings. This approach was used in the design of the Microspacecraft Technology Development (MTD) demonstration hardware (fig. 4) [Reference 30].

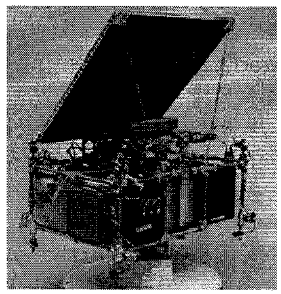

Figure 4. MTD Hardware

3.9 Aerocapture Technologies

The use of ballutes or aeroshells may significantly reduce the mass required to achieve orbit capture. While a conventional chemical propulsion system can require as much as 50–85% of the arrival mass to perform orbit insertion, studies indicate that the equivalent mass fraction of a ballute can be as low as 20% for some applications [Reference 31].

image processing requirements, and portions of the array can be selectively read-out, reducing data output (especially for sparse scenes).

5. Conclusion

While it is difficult to provide a detailed survey of current U.S. micro/ nanospacecraft technology and development activities in a paper of this limited length, the authors have attempted to provide a fairly comprehensive overview and sufficient references to allow the reader to seek out further details on his or her own. We hope that you find this paper useful.

Acknowledgements

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Background/Introduction

- ***Why is NASA Interested in micro/nanospacecraft?***
  - micro/nanospacecraft are expected to be cheaper to build and fly than conventional spacecraft
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- also, constellations or formations of micro/nanospacecraft can be robust to loss of any individual element, suffering performance degradation rather than failure of the entire mission

Overview of NASA Mission Applications of Micro/Nanospacecraft

- ***Applications and concepts for micro/nanospacecraft can be found throughout all areas of NASA endeavor***
- ***Applications are particularly driven where:***
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  - Risk is high (uncertain or hostile environments)
  - Simultaneous and/or distributed measurements needed or desirable
- ***Following are micro/nanospacecraft applications by NASA Directorate***

Overview of NASA Mission Applications of Micro/Nanospacecraft (continued)

- ***Earth Science (Code Y)***
  - Concepts of interest to NASA's Earth Science Enterprise include constellations or formations of micro/nanospacecraft for distributed or high-temporal resolution measurements
  - Current mission concepts that utilize microspacecraft include:
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  - For micro/nanospacecraft constellations, formation flight using micropropulsion is a key enabling technology
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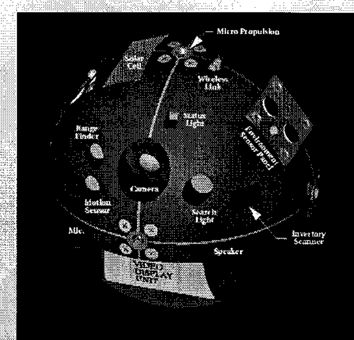

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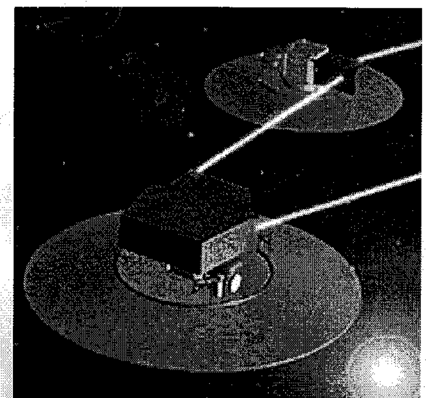

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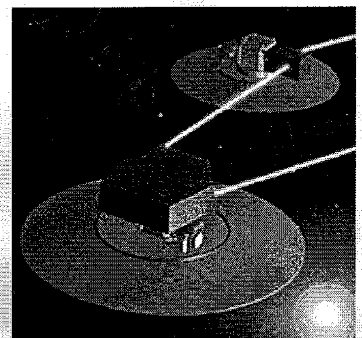

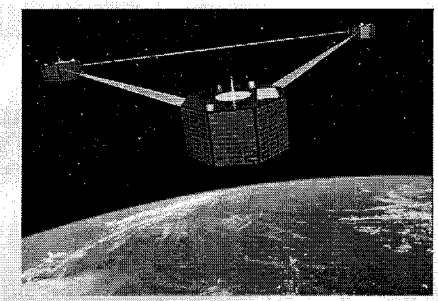

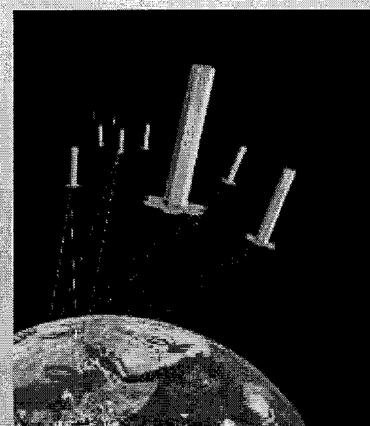

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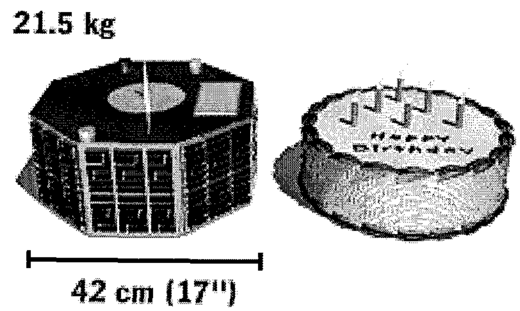

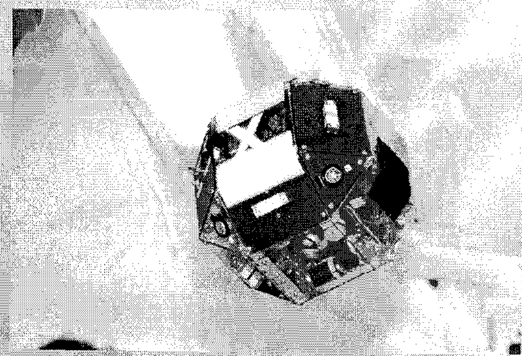

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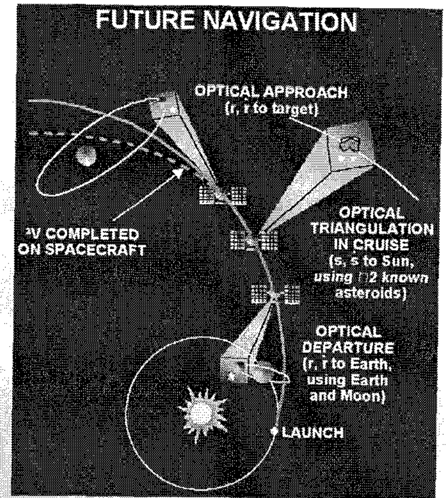

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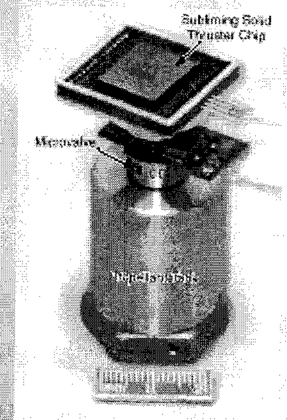

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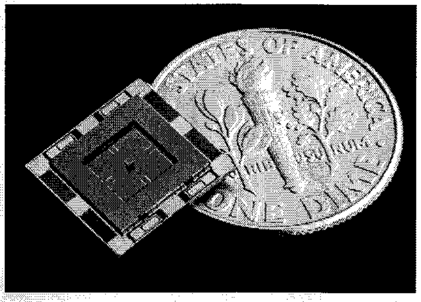

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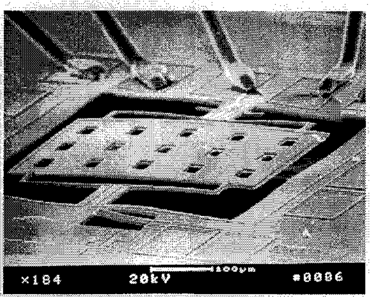
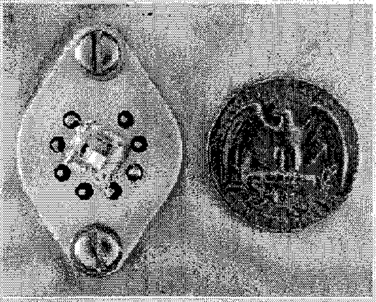




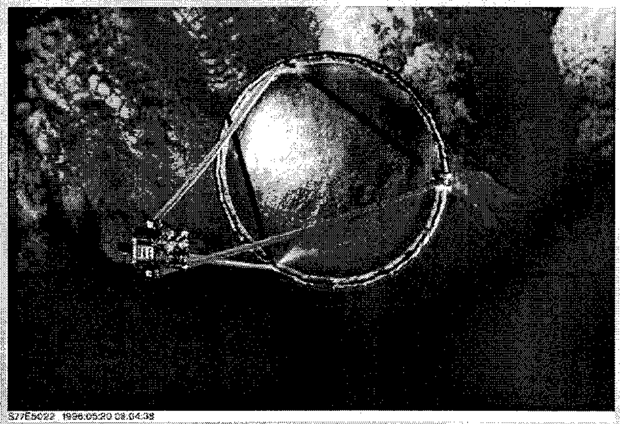
Current Development Activities (by Technology Area) -- continued

- ***Data Compression Technologies***

  Data Compression Technologies provide another option for reducing downlink requirements. The current state-of-the-art for "lossless" data compression is about 2:1, however research is ongoing into techniques that can achieve 1–2 orders-of-magnitude compression with some loss.

- ***Deployable Antennas***

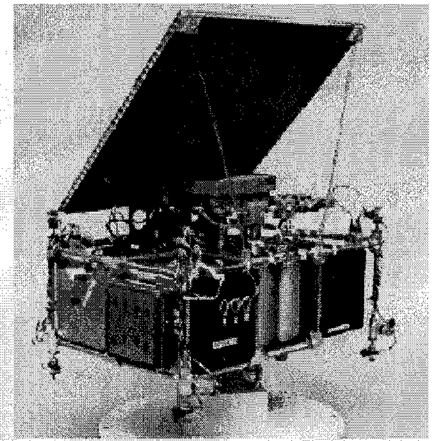
  Currently, mesh deployable antennas, such as the 12-m antennas built by Harris Corporation and flown on the ACES communications satellite and the 12.25 m x 16 m antennas built by TRW Astro Aerospace for the Thuraya Satellite, are the state-of-the-art for deployable RF communications antennas. However, the emerging technology of inflatable antennas offers potential for compact stowage of low-mass deployable spacecraft reflectors that are compatible with micro/nanospacecraft.



Current Development Activities (by Technology Area) -- continued

Optical Communications

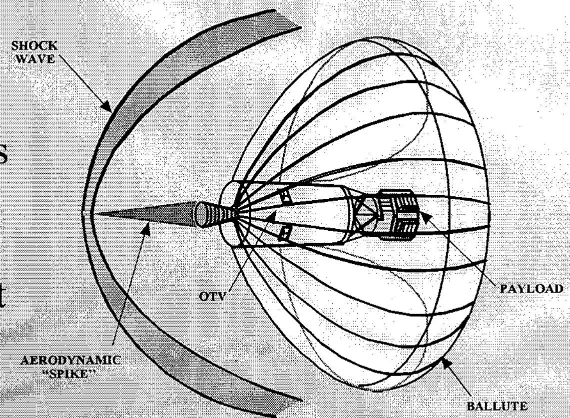
In some applications, optical communications systems can provide indirect savings in overall spacecraft mass via reduction in power system requirements as compared with an equivalent data-rate RF system.



Optical communications also present the spacecraft designer with the option of using the same front-end optics for both sensing and communications ("dual-use"), potentially resulting in significant system mass savings. This approach was used in the design of the Microspacecraft Technology Development (MTD) demonstration hardware.

Aerocapture Technologies

The use of ballutes or aeroshells may significantly reduce the mass required to achieve orbit capture. While a conventional chemical propulsion system can require as much as 50–85% of the arrival mass to perform orbit insertion, studies indicate that the equivalent mass fraction of a ballute can be as low as 20% for some applications.



Challenges, Issues, and Evolving Paradigms

- ***Technical Challenges:***

  Radiation, Micrometeoroids and Dust

  - *Conventional (large) spacecraft often rely on a few millimeters of structural aluminum and burying electronics deep within a spacecraft bus to provide radiation shielding to sensitive electronics.*
  - *Micro/nanospacecraft will not have millimeters of structural material to provide this protection, and may require selective and/or local shielding of radiation-sensitive elements.*
  - *Similarly, micro/nanospacecraft will also be more vulnerable to damage by dust or micrometeoroids.*

  Thermal Control

  - *Thermal time constants are much faster in small spacecraft, making thermal control more challenging. Adaptive thermal control systems are needed to accommodate widely varying thermal environments or large variations in internal heat dissipation. The dissipation of heat in compact electronics is a particular challenge for micro/nanospacecraft.*
  - *New technologies providing solutions to these challenges include miniature active cooling loops, thermoelectric cooling devices, micro heat pipes, and electrochromic materials.*

Challenges, Issues, and Evolving Paradigms (continued)

- ***New Paradigms for Micro/Nanospacecraft Design***
  - Minimize the Payload Requirements
    - *In addition to utilizing new developments in micro- and nano-instruments, approaches such as utilizing shared front-end optics among instruments can provide major benefits.*
  - Minimize the Telecom Requirements
    - *Data compression technologies and onboard processing of data are two approaches to reducing downlink demands. Significant savings were also achieved in the Second Generation Microspace-craft concepts through the total elimination of uplink capability.*
  - Take Advantage of Multiple-Use Technologies
    - *Very large mass, volume, and power savings have been demonstrated in concepts that utilize the same hardware to perform multiple functions. Examples include the use of minimum gage propellant tanks or high pressure tubing as load carrying structure and dual use of optical apertures for communications and sensing.*
    - *Active Pixel Sensor (APS) arrays can be utilized for multiple sensing functions ranging from star tracking (sensing dim sources) to imaging of bright targets, thus eliminating the need for multiple detectors. APS arrays can also be fabricated with on-chip processing functions such as centroiding, reducing image processing requirements, and portions of the array can be selectively read-out, reducing data output (especially for sparse scenes).*

Conclusions

- *NASA's potential applications of micro/nanospacecraft are diverse and pervasive throughout all areas of NASA endeavor*
- *Many of the technology development needs and challenges for these missions are similar to those for commercial applications*
- *U.S. NASA and Department of Defense microspacecraft technology development activities should also benefit commercial applications*

While it is difficult to provide a detailed survey of current U.S. micro/nanospacecraft technology and development activities in a paper of this limited length, the authors have attempted to provide a fairly comprehensive overview and sufficient references to allow the reader to seek out further details on his or her own. We hope that you find this paper useful.